Physical modelling to remove hydrological effects at local and regional scale: application to the 100-m hydrostatic inclinometer in Sainte-Croix-aux-Mines (France)

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Abstract. New inclinometers devoted to hydrological studies were set up in the Vosges Mountains (France). Two orthogonal 100-meter base hydrostatic inclinometers were installed in December 2004 as well as a hydrometeorological monitoring system for the 100-km² hydrological unit around the inclinometer. As inclinometers are very sensitive to environmental influences, this observatory is a test site to confront hydrological modelling and geodetic observations. Physical modelling to remove hydrological effects without calibrating on geodetic data is tested on these instruments. Specifically, two deformation processes are most important: fluid pressure variations in nearby hydraulically active fractures and surface loading at regional scale.

Introduction

Hydrological phenomena mix with geodynamical processes on a broad band of frequencies, ranging from long-term and annual variations, to short period disturbances of one hour (e.g. Evans and Wyatt 1984; Crossley et al., 1999; Zadro and Braitenberg, 1999). Some authors (e.g. Dal Moro and Zadro, 1998) concluded that hydrological effects should be removed before studying other deformation or dynamic signals.

Two methodologies have arisen to investigate hydrological effects. Both of them lead to relatively good results. They are however very different in terms of processes being modelled and spatial "extent" of the investigation:

i) The first one focuses on local deformation (Newtonian attraction for gravimetry). It is based on correlations between geodetic observations and local hydrological measurements - rainfall, piezometric, and soil moisture measurements (Bower and Courtier, 1998; Crossley and Xu, 1998; Kroner et al. 2001; Van Camp et al. 2006; Meurers et al. 2007). Both linear and nonlinear models have also been used (Wolfe et al., 1981; Yamauchi 1987; Latynina et al. 1993). In this case, fitting on (integrative) geodetic measurements somehow plays the role of "distribution" of the measured hydrological variable of local significance. Temporally speaking, this correction is a-priori limited by the temporal sampling of the environmental monitoring.

ii) A somewhat different deterministic approach considers the physical modelling of the contribution using global hydrological models (e.g. Lad World (Milly et al., 2002), or GLDAS (Rodell et al. 2004) considering global surface loading and Newtonian attraction. No calibration was made on geodetic data (Dong et al., 2002;, Boy and Hinderer, 2006). This methodology is limited by the spatial smoothing of global models (the tightest description is based on a 0.25° grid), and their temporal sampling. Note that Virtanen et al. (2006) has used hydrological models of several spatial extents in order to improve this approach.

This work is based on the fact that all environmental signals are correlated (especially on annual time scale), so calibration using geodynamic data could lead to incomplete correction of environmental noise (Tervo, 2006). As a consequence physical modelling is needed, *i.e.* every deformational process mixed in geodynamic measurements should be investigated separately. From a hydrological point of view both the amount and the position of water masses have to be modelled. This decoupling between geodetic deformation and hydrological modelling is the next step to accurate corrections of geodynamic time series (see Hasan et al., 2006; Longuevergne et al. 2006; Naujok, 2007). The possibility to use geodetic data as a tool for hydrology is at stake.

In order to investigate hydrological contribution to geodetic observations, a new observatory devoted to hydrological studies has been set up in Sainte-Croix-aux-Mines, in the Vosges Mountains (eastern France). We chose to install the geodetic instruments that are considered to be the most sensitive to environmental influences: inclinometers. Two processes of deformation induced by water generate significant geodynamical effects on recorded data: local hydraulic pressure fluctuations in nearby conductive fractures and surface loading at regional scale.

Spatial scales associated with hydrological effects

The earth is an elastic body that deforms under mass redistribution of different fluid layers on its surface (ocean, atmosphere, continental water). Surface loading has been studied for a long time in particular because of the indirect effects of oceans on the determination of tidal parameters (e.g. Bos and Baker, 2005). Each geodetic instrument has a different spatial sensitivity when dealing with loading process. Agnew (2001) investigated how instruments "see" a uniform surface loading. He has plotted "loading maps" using "deformational distance" for gravity, radial displacement, tilt and strain observations. This work has been followed by Llubes et al. (2004). They proposed 3 scales of interest which must be considered when dealing with environmental loading (see Figure 1): global scale, i.e. mass redistribution on the entire earth, regional scale, i.e. distances between 1 km and 10 km, and finally local scale, 1 km around the instrument. We keep the same scales as reference for all deformation processes. Orders of magnitude of observed deformation determined from previously cited works are indicated in Table 1.

Table 1: Spatial scales associated with different geodetic measurements and associated orders of magnitude (from previously cited works and this work)

	Local	Regional	Global
GPS	negligible	negligible	10 mm
Gravimeters	50 $nm.s^{-2}$	negligible	50 $nm.s^{-2}$
Inclinometers	500 nrad	50 nrad	negligible

Inclinometers devoted to hydrological studies

The choice of the installation site is a first consideration to record good data, and requires special care (e.g. Melchior, 1973). An old mine was chosen in Sainte-Croix-aux-Mines (Vosges Mountains, east of France). Figure 1 shows the two orthogonal branches of the mine. The mine excavated into gneissic rocks and the 160-m height rock covering, ensuring the environment to be very stable (temperature variation is around 10^{-1} °C over the year). We set up two orthogonal 100-m base hydrostatic inclinometers, based on the communicating vessels' principle (see Agnew, 1986), using a design recently developed by Boudin (2004). The N37°E instrument has been monitoring crustal tilting since December 2004 with a temporal sampling of 30 seconds and a resolution better than 10^{-10} radians (0.02 mas).

It is notable that a perfect coupling between gneissic rock and instrument has been achieved. This is important since the use of inserted material is considered as responsible of important drifts (see figure 2 for raw data). The data has proved to be of good quality for both long-term and short-term monitoring (see Boudin et al., 2007 for normal modes generated by 2004 Sumatra-Andaman earthquake). Unfortunately, several lightning and associated electrical problems have to be reported, which caused the gaps in time series.

In the same time, the hydrometeorological monitoring of the 108 km² hydrological unit (catchment) around the instrument has been set up in order to monitor mass balance as precisely as possible. A meteorological station has been installed. The studied catchment receives a total rainfall amount of 1300 mm a year, and an important horizontal rainfall gradient is also observed (80 $mm.km^{-1}$). To take into account this spatial variability, 15 daily-sampling raingauges are used in this study. A single raingauge near the inclinometer would have underestimated the total rainfall of 10% (see Figure 1 for annual rainfall amount). Daily stream flow at the outlet of the catchment is measured by the French direction for environment (DIREN).

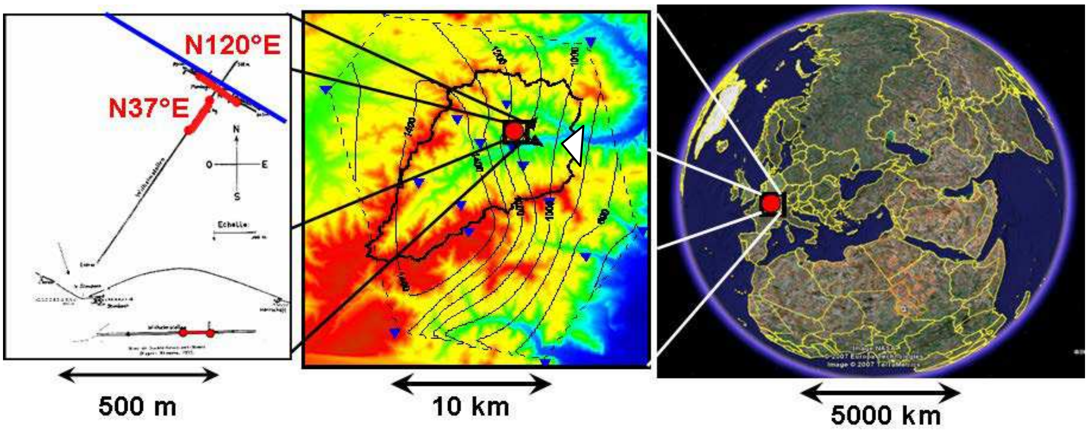

Fig.1: Situation of inclinometers and illustration of spatial scales. On the left, local scale and installed instruments in their environment. The N37°E inclinometer is installed orthogonal the metallic vein (dark blue line), the N120°E inclinometer is installed inside the exploited metallic vein. In the centre, regional scale illustrated with colored topography. Contours are yearly rainfall [mm], thick line is the limit of the studied catchment, the triangle at the outlet is the water flow measurement. On the right, global scale.

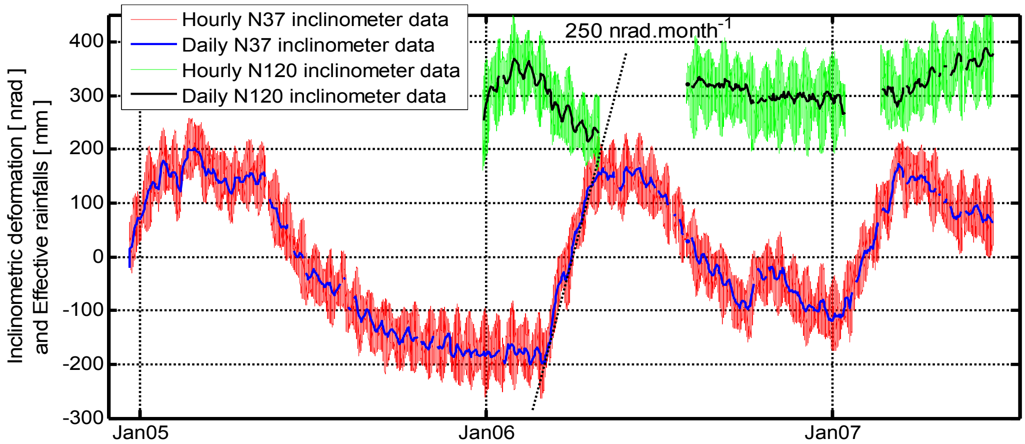

Fig. 2: Raw data of both orthogonal inclinometers (N37 instrument below, N120 instrument above). Note the 100-nrad amplitude tides, and the repeated 250 nrad.month^{-1}-"drift" during 2 monthes on N37 instrument only.

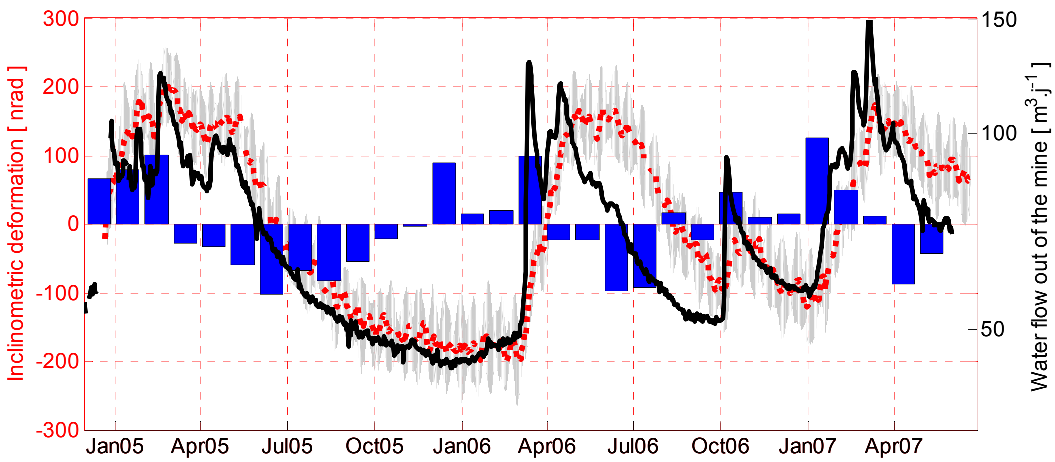

Fig. 3: Daily decimated N37°E tilt signal (dotted red curve) vs. logarithm of water flow out of the mine (continuous black curve). Blue bars are estimated monthly time derivative of stored water variations (i.e.Rainfall minus .potential evapotranspiration minus runoff)

Local scale deformation

The comparison between water drainage out of the mine and daily decimated tilt time series (see Figure 3) shows that hydraulic pressure variations in nearby conductive fractures generate the major part of the recorded deformation. Evans and Wyatt (1984) attributed this deformation to the change in the aperture of a hydraulically active fracture. Indeed, 20 m from the north vessel the exploited metallic sulphide vein plays the role of a preferential path for water. Because of the limited thickness of the fractures, an influx of water induces a quick variation of water height, and thus a quick variation of pressure.

The signature of this deformation is the 250 nrad.month-1 quick variation during 2 months on the N37°E instrument, orthogonal to the fracture, and very few effect on the N120°E instrument, installed quasi-parallel to the fracture (see figure 2, in April 2006, October 2006 and February 2007).

The quantification of this deformation can be seen, as a first step, with first order models. Mechanically speaking, deformation is linked to water height variations in the fracture. Hydrologically speaking, water flow is linked to the exponential of water height variations, *i.e.* water height variations is linked to the logarithm of water flow, the hydrological units having an integrative behaviour. These considerations are plotted on Figure 3.

The water supply of these fractures is driven by the hydrological unit on top of the hill. Geophysical studies show 10 to 20-meter deep altered gneiss (*i.e.* ≈ sand) covering a fractured media. Soils have the capacity to absorb water before letting it infiltrate. As a consequence, they play the role of a low-pass filter concerning water infiltration. This explains the long term contribution of this local hydrological unit. The quantification of this deformation without calibration on geodetic data is difficult, for both hydrological and mechanical reasons. Firstly, the mine drainage gathers water that does not come from the deforming fracture. Secondly, is it necessary to correctly model this hydromecanical deformation and the joint behaviour. In the following work, this deformation has been "corrected" thanks to the calibration of the logarithm of mine drainage on geodetic data. As a consequence, long term corrected data is affected by this approximate correction.

An accurate calculation of the fracture deformation will need further studies, on both mechanical and hydrological considerations.

Regional scale deformation

Inclinometers are sensitive to surface loading at regional scale. As a consequence, we study the unit of hydrological significance of the same size, i.e. the 108-km² catchment around the instrument (see figure 1 – regional scale).

We use the Green function formalism to calculate tilt deformation induced by stored water variations within the catchment (Farrell, 1972; Pagiatakis 1990; Guo et al., 2004). This calculation needs both the amount (i.e. the stored water variations) and the location of water masses.

Amount of water.

A robust calculation of the mass balance within the catchment relies on the capacity to assess realistically each part of the hydrological cycle at catchment scale: $\frac{dS}{dt} = P - AE - (Q + Q_{sub})$, where $\frac{dS}{dt}$ is the time derivative of stored water on the earth crust, P is precipitation rate, AE actual evapotranspiration rate, and finally $Q + Q_{sub}$ the runoff amount, respectively surface runoff and subsurface runoff (e.g. Lettenmaier, 2005).

Evapotranspiration is a nonlinear process that is difficult to measure directly (e.g. Strangeways, 2003). Subsurface runoff may also be a substantial part of surface runoff (e.g. Le Moine et al., 2007). Thus we chose to assess water losses by calibrating a rainfall-runoff hydrological model. We use the 4-parameter lumped model GR4J (Perrin et *al*., 2003). The model is calibrated using the daily streamflow measured at the outlet of the catchment. The Nash and Sutcliffe (1970) criteria is up to 0.8 in calibration (1 indicating a perfect description of the reality). More details may be found in (Longuevergne et al., 2006).

Position of water masses.

The second part of our methodology consists in distributing the determined stored water layer over the catchment surface. This question is important because a tiltmeter is an oriented instrument. In the following work, we have assumed stored water variations are located in the bed of the valleys.

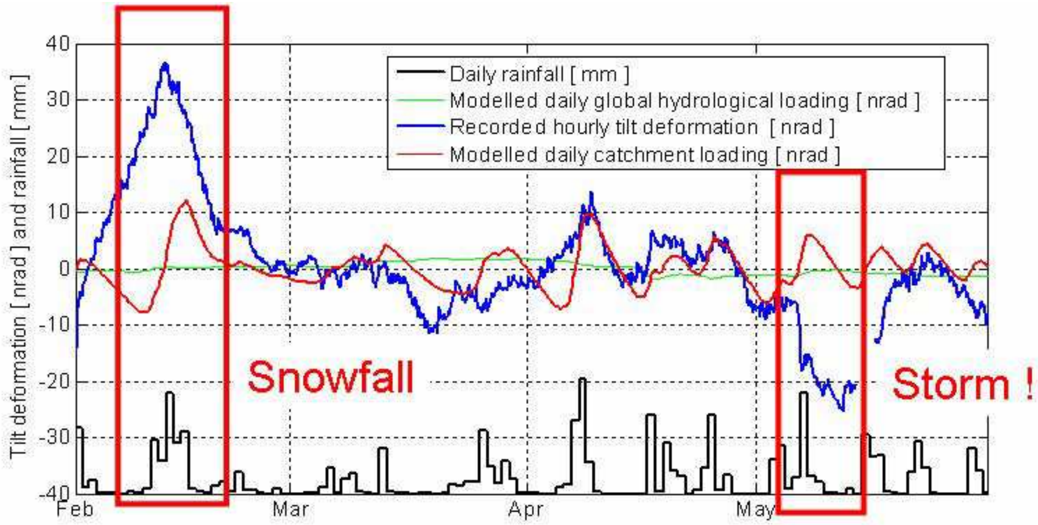

Fig. 4: Predicted modelled regional surface loading in light red vs .recorded N37°E tilt signal (dark blue curve). For more clarity, the zero of precipitations is taken to be -40. Global scale hydrological loading has also been calculated, its long-period contribution is negligible (light green curve).

Comparison between model and observations.

The discrepancies between modelled and observed deformation help to understand the difficulties associated with hydrological surface loading (see figure 4). Indeed, the inclinometer is a "differential balance" between what is north and what is south to the instrument, that is why it can detect when the hydrological behaviour of the catchment cannot be considered as uniform (snow accumulation periods, storms observed only in the northern part of the catchment in May). On the contrary, the predicted regional deformation is in good agreement when the catchment behaviour can be considered as "homogeneous" (i.e. stable precipitation field).

As a consequence, inclinometers may be seen as a tool for the validation of more complicated distributed hydrological models, since they are sensitive to the position of water masses inside the hydrological unit.

Discussion

The modelling of hydrological contribution to geodetic observations is difficult since all environmental signals are correlated and mixed differently in geodetic measurements. As a consequence, the use of simple physical models (Longuevergne et al., 2006; Meurers et al., 2007), as well as hydrological experiments to focus on single process (Kroner and Jahr, 2006) are very helpful to estimate good orders of magnitude and understand "what is happening". When looking at monthly time derivative of stored water variations plotted on Figure 3 (i.e. measured rainfall minus measured .potential evapotranspiration minus measured runoff), it seems that the agreement with tilt data to be correct after time integration. Unfortunately, surface loading is of the order of 50 nrad, and cannot explain alone the 500 nrad recorded deformation.

Note that global hydrological loading has also been evaluated using GLDAS (Rodell et al., 2004) global hydrological model. This deformation is only 4 nrad (see figure 4).

Conclusions

We have proposed a methodology to physically model the hydrological contribution to geodetic signals without calibrating on geodetic data. It is based on a 3-step approach:

1. Determine deformation process and control the mechanical (or dynamical) behaviour at the spatial scale of the deformation.
2. Calculate the amount of water in the associated hydrological unit using hydrological models adapted at the spatial scale of interest.
3. Evaluate the position of water masses

Concerning surface loading at regional scale, results show that modelled short-term fluctuations of stored water are consistent with inclinometer measurements, when the spatial distribution of water within the catchment can be considered as “constant" (i.e. stable precipitation field in time). Conversely, large discrepancies exist during storms and snow accumulation periods because the inclinometer is also sensitive to the position of water stored within the catchment. As a consequence, we believe that geodesy could bring interesting additional information on both the quantification and the distribution of water within the catchment. Geodesy could therefore become an interesting tool for hydrological studies, i.e. provide a better understanding of hydrological processes and a more accurate calibration of hydrological models.

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